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Modelling subgroup behaviour in crowd dynamics DEM simulation

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ABSTRACT

This paper investigates the behaviour of subgroups in crowd dynamics by means of filming and observation. An existing crowd modelling program, CrowdDMX, based on a discrete element model (DEM) has been modified on the basis of observations made in this paper and literature. Each person is represented as three overlapping circles and motion is modelled in a Newtonian manner. It incorporates psychological forces as well as physical forces in a 2D time-stepping environment. The DEM model was modified to include realistic subgroup behaviour, representing people in the crowd desiring to stay together (families, friends, etc.). Subgroup psychological forces were incorporated. The previous model only simulated individuals moving independently, which was unrealistic in some situations as shown by the observation and filming part of the study. The revised program models subgroups realistically including the tendency to avoid subgroup division in cases of contra-flow.

1. Introduction

1.1. Requirement for crowd dynamic simulation

Crowd dynamic simulation includes the modelling of crowd movements and their interaction with the people around them and the physical environment. The issue of crowd dynamics is important for the safe design of venues where crowd management is a major issue. Such venues include large stadiums, theatres, railway stations, subways and other places where effective positioning of entry and exit points is required. Crowd simulation models help in effective prediction of potential crowd hazards in critical situations and thus help in reducing fatalities.

In recent years there have been many crowd related tragedies [1,2]. For example in India in 2005, 258 people lost their lives during a crush at a Hindu religious festival; and in 1986, 96 people were killed at a crowd crush at a football match at Hillsborough Stadium in Sheffield, UK. A different example is a laptop sale at a race course in Richmond, Virginia, USA in August 2005, when used Apple notebooks were on sale for a vastly reduced price. An estimated 5500 people attended, and a 'violent stampede' ensued as individuals rushed to get through the entrance [3]. Such disasters could be avoided or losses reduced by using crowd simulation models. The growing terrorist threat also increases the risk of a crowd tragedy. Thus it is important to enhance the accuracy and prediction capability of such simulation models.

1.2. Crowd psychology

The most effective studies into crowd behaviour incorporate both psychology and engineering. An appropriate approach is that of environmental psychology, where the relationship between people, physical and social settings are considered [4].

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Perhaps the most influential work in this field is that of Fruin [5], which examines the relationship between such factors as space per person, speed of movement, flow, and social acceptability. By applying to pedestrian movement the 'level-of-service' concept used in highway engineering, Fruin's approach specifies the degree to which individuals within a crowd are able to move at different speeds and in different directions to those around them.

More recently, Cooper et al. [6] suggest that there are three governing psychological factors which influence crowd movement. The first is that each person is trying to reach a specific geographical goal. The second is that people will walk at a maximum speed dependent on certain environmental conditions. The third is that a discomfort zone exists; this means that if all things were equal then someone would rather be at one point over another. This can also be thought of as personal space. These three factors all interact with each other to determine the path a person in a crowd will take when considering how to reach their desired position. Once these and other factors governing the crowd behaviour – including leadership, emotional intensity and collective unity of purpose [7] – have been established, the crowd's behaviour can be anticipated. Both individual and collective human behaviour can be predicted, as it is largely rational and goal orientated; and as time evolves a hierarchy of goals is formed and these influence the decisions that the person will make. It is for this reason that crowds can be modelled using rational computer programming [1].

The typical approach towards studying crowds conceives them as a collection of individuals who are undergoing some common experience [8] but does not always consider smaller subgroups of people within the crowd. However, the issue of groups within a crowd has not been totally overlooked by social scientists, who recognize that a 'physical' crowd may be made up of more than one 'psychological' crowd or group [9–11]. However, this observation has played a relatively small part in the modelling of crowd dynamics. If people interact with a crowd as part of a group rather than as individuals, then it may be appropriate to extend crowd analysis beyond the inter-individual level. Aveni [12] conducted a study into the relevance of considering subgroups within a larger crowd by periodically interviewing members of the public attending an American football game. The findings of this study indicated that only a quarter of the people in this crowd were actually by themselves, thus showing that the majority were not isolated, anonymous individuals. More recent research across a range of types of crowd events has supported this finding. Thus it has been show that (a) many people in crowd events are known to each other rather than being anonymous [13]; (b) large crowds such as those at sports events are sometimes made up of opposing factions, who act and move collectively yet against other groups in the crowd as a whole [14]; and (c) the extent to which people in a crowd operate and behave as individuals versus in subgroups or collectively varies over time and place [15].

These observations clearly have implications for the modelling of crowd behaviour. Therefore in order to accurately simulate crowd movement through computer programming, two inter-related levels of analysis are required; one for individuals and one for groups.

1.3. Crowd dynamics simulation models

Zheng et al. review [16] current methods of modelling evacuation including cellula automata, fluid models, social forces and agent based (which includes discrete element). The models include aspects of group and individual behaviour. Jianyong et al. [17] combine a Computational Fluid Dynamics model of fire with an agent-based evacuation model and a case study was applied to an indoor stadium used in the Beijing Olympics. They indicate that group characteristics are one of the issues that affect evacuation. Fang et al. [18] observed crowd behaviour at a railway station in China. They conclude that the crowd speed is primarily a function of front-back inter person spacing and individual motivation. Spieser and Davison [19] apply control theory to show how authoritative figures interspersed in a queuing crowd can stabilise the crowd given good communication between the controlling agents. Deere et al. [20] gives general information of a model maritimeEXODUS to assess the impact of human factors in ship design. It incorporates a number of sub-models such as hazard and movement, the most complex one is on behaviour which incorporates reaction to communication and affiliative behaviour. It uses a concept of "genes" to model social relationships, group behaviour and hierarchical structures. The group members are identified through the sharing of social "genes". Gwynne et al. [21] compares buildingEXODUS predictions with data from large building evacuation trials. Both qualitative and quantitative agreement was obtained. It highlights that many crowd models lack detailed validation data. Likewise Galea [22] has argued that, for greater realism in modelling, more observational and interview data on group behaviour within crowds is necessary. Moore et al. [23] investigate the effect of alcohol on behaviour, aided by a particle-model of crowds. Their simulations are consistent with the idea that alcohol disrupts affiliative behaviour shown by less structure in crowd flow, but also concludes more field data is required. Details of two major UK crowd dynamics simulation packages are available on the web [24,25].

One engineering approach to crowd dynamics is to model people in a "particle-like" manner, paying less attention to the psychological and social interaction between individuals [4]. In real life movement of individuals within a crowd is often dictated by the movements of the group as a whole. This collective motion of many people displays similarities to Newtonian particles such as phase transitions, cluster formation and occurrence of domain walls [26]. Due to this, several attempts have been made to model crowds as fluids on a macroscopic scale [27,28]. Fluid flow is determined by physical forces whereas crowds do not necessarily satisfy Newton's third law (i.e. the law of action and reaction) as they are also influenced by psychological factors. Therefore these methods are insufficient in situations concerning multiple groups and contra-flow. A preferred method therefore is to use a microscopic approach which models each individual, such as the Discrete Element Method (DEM).

DEM has been used extensively to simulate granular flows [29–31] by numerically integrating particle acceleration resulting from contact forces experienced. The principle of DEM is to track, in a time stepping simulation, the trajectory and rotation of each element in a system to evaluate its position and orientation, and then to calculate the interactions between the elements themselves and also between the elements and their environment. The interaction will then subsequently affect the element positions. DEM is also potentially capable of simulating complex boundaries and three-dimensional objects such as staircases and buildings. With modifications to include psychological forces, this method can also be implemented in crowd dynamics with the advantage that relatively basic data can be used without oversimplifying assumptions. To include these psychological factors, a general psychological radius (i.e. personal space) surrounding each person can be set [32] (Helbing et al., 2000).

DEM has been implemented specifically in the area of crowd dynamics in the CrowdDMX model [33] (Langston et al., 2006). The DEM technique has been applied in a 2D environment modelling a number of forces. The main forces used are

- A psychological interaction force taken from Helbing et al. [32].
- A normal force experienced on contact which is modelled as a linear spring [32].
- A sliding friction force modified from the equations used in Helbing et al. [32].
- A physical damping force proportional to the normal relative velocity.

Each person within the program is represented by three circles; one large circle for the body and two smaller circles for the shoulders. Also incorporated in the program are moments on individuals resulting from physical contact, a motive moment, i.e. how an individual will turn to face a desired direction, a motive force and an individual's motion, i.e. resultant translational and angular acceleration. Hence the program simulates movement and decision making by means of adding the psychological forces to the physical forces, although it does not explicitly include decision making as could be modelled in say a Monte-Carlo process using random numbers [16].

The aforementioned program [33] (Langston et al., 2006) did not account for people travelling in different directions. Therefore when two people met head-on in contra-flow, unrealistic collisions occurred. To overcome this problem an avoidance model was written into the program by Smith et al. [34]. This meant the desired velocity of a person could be changed in order to avoid potential collisions detected by the program. A summary of the previous models is provided in Appendices A and B.

1.4. Inclusion of associative subgroup behaviour in DEM model

The DEM model uses the concept of a '*group*', defined as a physical collection of people following the same route, but who may or may not be part of the same social group. Whereas the present paper defines a new term, '*subgroup*', defined as people within the same *physical* '*group*' who want to stay together.

Studies have revealed that smaller subgroups like those of friends or a family constitute the majority of the people in a crowd [12,13]. The CrowdDMX model was limited to modelling individuals independently. This led to discrepancies in the simulation with unrealistic splitting of subgroups. Video footage obtained compared with the simulated scenario clearly showed this problem to be significant. In order to correct this limitation, the ability to simulate groups of friends or families moving in a crowd was added to the model. This paper focuses on a two-step approach adopted for this modification

(1) Observation and filming of crowds in mundane situations to obtain accurate evidence of subgroup behaviour.
(2) Novel algorithmic changes to CrowdDMX program including
    - Additional aim points for members of a subgroup alongside the nearest neighbour.
    - Psychological repulsive forces between two subgroups, treating them as single units.
    - Additional psychological force on an individual encountering a subgroup.

These changes led to more realistic simulation as verified by comparisons with real-life video footage as shown in this paper. The subgroups were defined for the simulation according to what was observed in the filmed footage. Essentially the simulation was set up to correspond to the initial boundary conditions observed, and then the model ran and results compared with the later stages to see how well the subgroup behaviour is replicated.

1.5. Summary of study

This paper comprises four sections. Section 2 describes the observational study and filming of crowd behaviour in public places. By noting critical attributes of subgroup movement, guidelines are postulated for the incorporation of subgroup modelling in the DEM technique. Section 3 describes in detail the modifications made to the CrowdDMX program. The algorithmic details include the methods for input and creation of subgroups in the simulation, the intra-subgroup motive forces to keep the subgroup intact, inter-subgroup repulsive forces and subgroup–individual repulsive forces. The equations postulated and implemented are described. The validity of the algorithm is demonstrated using three different scenarios wherein video footage is compared to simulations initialised to the same scenarios. The conclusions and recommendations for further development are presented in Section 4.

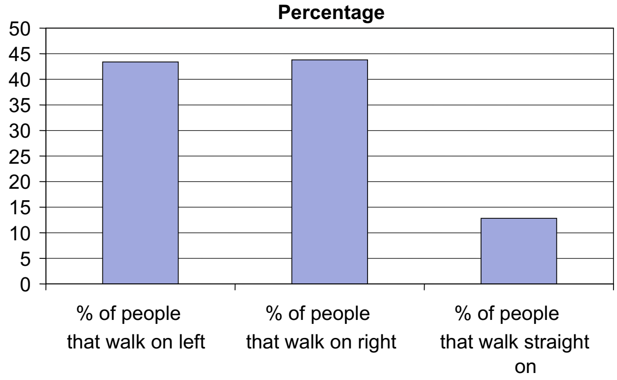

Fig. 1. The side of the path that individuals and subgroups walked on in the filmed footage.

2. Observations and filming of crowds

This study observed about 3500 people. Around 1000 of these people were observed on the filmed evidence, and the remaining 2500 were observed in Nottingham city centre.

2.1. Filming crowds

A large part of this study involved filming crowds in various locations around The University of Nottingham main campus and then analysing the footage. Filming occurred on three parts of the main campus: an area filmed from a bridge connecting the campus with the Queen's Medical Centre, an area filmed from a balcony on the Chemistry Building and an area filmed from a platform on the Pope Building. These locations were chosen as they were long straight stretches of pathway, where it was possible to view people for a sufficient length of time to see their behaviour after avoidance action had to be taken. These locations were filmed on several occasions to ensure that any data found from the footage was as accurate and reliable as possible.

The footage was evaluated quantitatively for the number of people, the number and size of subgroups present, as well as for preferences in the side of the path people walk on and in the way avoidance action is taken. These parameters were chosen as they were highlighted in literature as being limitations within existing models and areas where there is a lack of knowledge within crowd dynamics [11]. As well as this quantitative analysis, any trends observed in the footage were also noted.

From the filmed evidence, in which about 1000 people were studied, it was found that people prefer to walk to one side of a path, with only 14% of the people studied walking down the centre of a path. Of the other 86%, almost equal numbers chose to walk on the left and on the right (defined in terms of travel direction), showing that there is no preferential side of walking – see Fig. 1.

When studying the footage obtained for the way that avoidance action is taken, it was clear that if a person is walking to the left or right of another person, then they will avoid colliding with them by remaining to the left or to the right. However if they are walking straight towards another person or a subgroup of people, then there are three different ways in which avoidance action is taken. Forty-four percent of the time, a person or subgroup will move to the right to avoid colliding with others and 34% of the time they will move to the left. The other 22% of the time, a subgroup will actually split to avoid colliding with people they are walking towards – see Fig. 2.

As well as the above findings, several other trends or patterns have been identified from the research footage. The first observation is that a subgroup of people will usually avoid splitting if possible. This may mean that they will crowd closer together, or even collide with other people, to avoid becoming separated. An example of this kind of behaviour can be seen in Fig. 3. The two people in the subgroup circled in green, in the first picture, are walking up the path towards a subgroup of three walking in the opposite direction (circled in red).[1] In the second picture it can be seen that rather than split up, the people in each subgroup move closer toward their companions and allow members of the other subgroup to enter their personal space. This therefore displays a preference of subgroups to remain together.

Another finding is that an individual person is more likely to walk around a subgroup of people than walk through the middle of them. Fig. 2 shows that only 22% of groups will split to avoid colliding. This trend substantiates the aforementioned observation, as it reinforces the concept that subgroups desire to stay together. The first picture in Fig. 4 shows a subgroup of two circled in red and a single person circled in green. To avoid colliding with and splitting the group of two, the individual person not only moves aside but also steps onto a raised wall, highlighting the behaviour described above.

[1] For interpretation of the references to colour in Figs. 3 and 5, the reader is referred to the web version of this article.

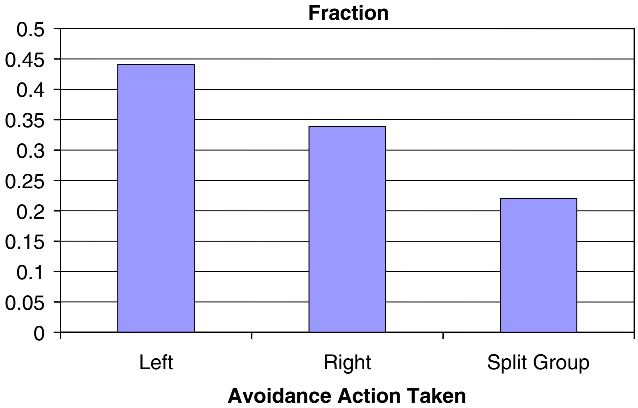

Fig. 2. The avoidance action taken by people walking straight towards others.

Fig. 3. Filmed footage illustrating subgroups grouping together closely and allowing others into their personal space to avoid splitting.

Fig. 4. Filmed footage showing a person circled in green stepping onto a wall to avoid a subgroup of two. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When a subgroup does split, it is because there is an obstacle of some kind to avoid, usually another person or subgroup. In the situation where there is more than one obstacle to avoid a subgroup will not regroup between them. Instead the subgroup will remain apart and regroup only after all obstacles have been avoided. This kind of behaviour is demonstrated in Fig. 5. A subgroup of two (circled in red) can be seen splitting a subgroup of four (circled in green) in order to avoid a collision. In the next picture, it can be seen that the subgroup of two has passed through the subgroup of four and now

Fig. 5. Filmed evidence of a subgroup splitting, avoiding people walking towards them and only regrouping after all obstacles have been passed.

Fig. 6. Filmed evidence demonstrating the tendency of people to follow others.

an individual person (circled in blue) is causing the subgroup of four to remain separated.[1] The third picture shows the subgroup of four finally regrouping after the individual had passed, i.e. after all obstacles had been avoided.

The final trend observed is that people are likely to follow others in front of them. They will walk on the same side of the path as other people in front of them and they will take avoidance action on the same side. This can be seen in Fig. 6 where the people circled in red are all walking in the same direction, on the same side of the path.

2.2. Observing crowds

The second part of this study was based on research carried out by Aveni [12] described in Section 1.2. This research was carried out in the 1970s and only took into account one crowd at a sports event. More recent studies of subgroup behaviour within crowds have focussed on unusual crowd events, such as riots and demonstrations [13–15]. We therefore felt that it was important to carry out similar observational research on mundane crowds in a variety of different locations to see if subgroups make up a large proportion of crowds in different situations.

To carry out this research the numbers of subgroups of certain sizes, within a designated area, were recorded every 10 s for half an hour. This was carried out in three locations in Nottingham city centre: Broadmarsh Shopping Centre, Clumber Street and Nottingham Railway Station. These places were chosen as they represent crowds in two types of situations; shopping and travel. The earlier research at Nottingham University shows crowds in a study or work environment, which is a third situation studied. As with the first method of research, the crowds in these places were studied on many different occasions to ensure that the data collected is as accurate and reliable as possible.

Fig. 7 shows the results from the research into subgroup sizing. It shows that for any of the crowds studied, a large proportion of the crowd is made up of subgroups of two or more people. The percentage of people in a subgroup ranges from between 63% and 67% for a shopping environment (Broadmarsh shopping centre and Clumber Street), 56% for a travel environment (Nottingham train station) and 47% for a work or study environment (Nottingham University). The crowds with the largest proportion of people in a subgroup of two are those in the shopping areas, whilst the university had the highest proportion of subgroups of three and the railway station had the highest proportion of subgroups of four or five. It can therefore be plausibly concluded that a large portion of people in any crowd are indeed part of a subgroup of people and it is therefore important for any crowd modelling program to include these 'subgroups' in order to carry out realistic simulations.

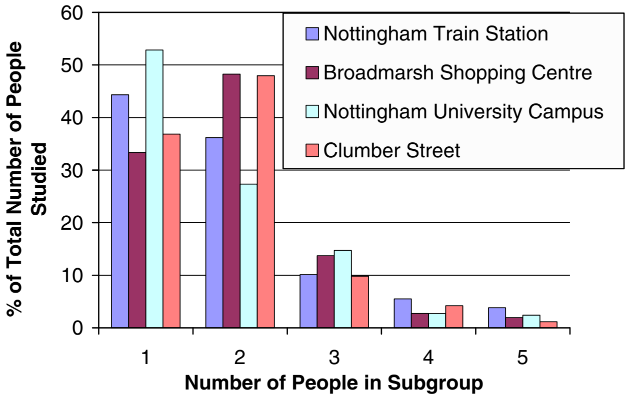

Fig. 7. The sizes and proportions of subgroups within a crowd.

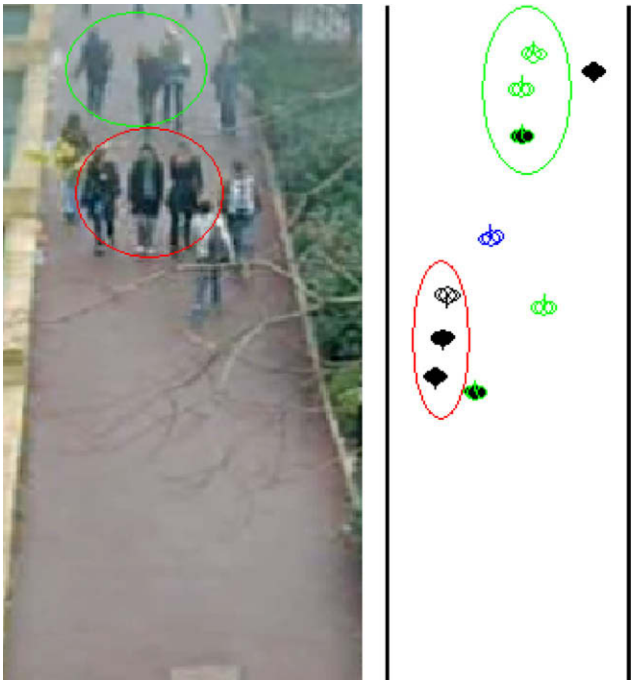

Fig. 8. Simulation of the video footage shows that the people circled do not remain in their subgroups with the original program. Note that in the simulation snapshots in this paper the person shading and colour has no significance other than helping to identify individuals in a time sequence.

3. Model development of subgroups

From the study of previous work on crowd dynamics [12,34] and from filming and observing crowds, the absence of smaller subgroups in the present Crowd DMX program was found to be a significant limitation, as shown for example in Fig. 8. These subgroups might represent friendship groups, colleagues or any persons who wish to walk together and will regroup after avoidance action has been taken. These subgroups have been found to make up a large part of every crowd and yet people in the crowd DMX program were only considered as individuals. To correct this limitation, the program was modified as described here.

3.1. Creation of subgroups – formation attractor points

The previous Crowd DMX program [33,34] simulates groups of people, but here we define a new term *subgroup*. It is important to clearly distinguish these terms in this study.

- A *group* has the same starting location and path of travel defined by a series of zones and their *attractor points*. But people in each group behave independently according to the situation.

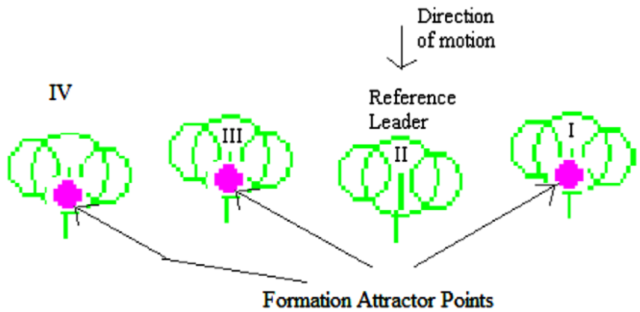

Fig. 9. A diagram showing a subgroup. Formation attractor points are shown in pink. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- A *subgroups*, is a sub-set of a group. It is *defined* as *a number of people that desire to stay together.*

It is important not to confuse this idea of a subgroup with that of the aforementioned groups.

This concept is introduced by setting *secondary attractor points* (or *formation attractor points* as they hold the subgroup in formation) for members of a subgroup fixed relative to a neighbour of the same subgroup. An assumption made for the simulation is that a subgroup consists of *at most four* people. The observations in Section 2 showed that this is generally the case. Relative positions of the formation attractor points are set according to the following formulae:

$$A_{fx} = r_{Lx} \pm d_r \cos(\theta), \tag{1}$$

$$A_{fz} = r_{Lz} \pm d_r \sin(\theta), \tag{2}$$

where (A_{fx}, A_{fz}) are the coordinates of the formation attractor point of each member, (r_{Lx}, r_{Lz}) are the coordinates of relative neighbour, d_r is the desired distance between two consecutive members, θ is the desired angular orientation of the subgroup.

To decide the relative neighbour, the 2nd person (from the left, if all members are held in a line formation), is taken to be the reference leader. Subsequently, the relative neighbour for the 1st and 3rd persons is this reference leader while the 3rd person is the relative neighbour for the 4th person. It is to be noted that a subgroup may have less than four people Fig. 9 shows a graphical representation of a subgroup.

Each member of the subgroup moves independently towards the attractor point of the group, yet each, except the Reference Leader, also have a desired velocity component towards their individual formation attractor points. These members will henceforth be mentioned as the *followers*. Hence, the subgroup remains together.

The user of the program is allowed to enter subgroup details manually or to generate random scenarios.

3.2. Intra-subgroup motive force

There are situations in real crowds where people deliberately change their velocity, for example, they may slow down approaching stairs or speed up given favourable terrain. In CrowdDMX this is replicated by means of a motive force. Given the desired velocity V_D of a person, the motive force on the individual is calculated from the formula [31]:

$$F_M = m_i(V_D - V_i)/\tau_i, \tag{3}$$

where V_D and V_i are the desired and actual velocities of person i, τ_i is the characteristic time (an empirical value which determines how quickly a person responds to a situation), m_i is the mass of person i.

The intra-subgroup motive force is incorporated into the model using the same formula, except the desired velocity, V_{SD} is calculated using the equation:

$$V_{SD} = V_D + k_{sd}d, \tag{4}$$

where V_D is the original desired velocity of the follower, k_{sd} is the subgroup velocity constant, d is the distance of the follower from his/her formation attractor point.

The effect of this equation is that the greater the distance between a follower's formation attractor point and the follower, the greater the change in the follower's velocity. This is set to simulate the behaviour of people trying to catch up if they lag behind the leader or slow down if they get ahead. The constant k_{sd} was found to be most realistic with a value of 0.15 s^{-1} as this displayed a desire of the follower to return to their formation attractor point but did not result in an unrealistically high velocity at small distances. Fig. 10 illustrates the principle of Eq. (4) in order to maintain the subgroup. This incorporates the tendency of a follower to stay close to his/her neighbour by staying on or close to the formation attractor point. An interesting trait of the simulation is that it captures the breaking away of an individual from a subgroup to make his/her own way. If the distance between follower and his/her attractor point becomes greater than 5 m then the follower is set to revert back to being a leader and following the fixed attractor points for his/her group.

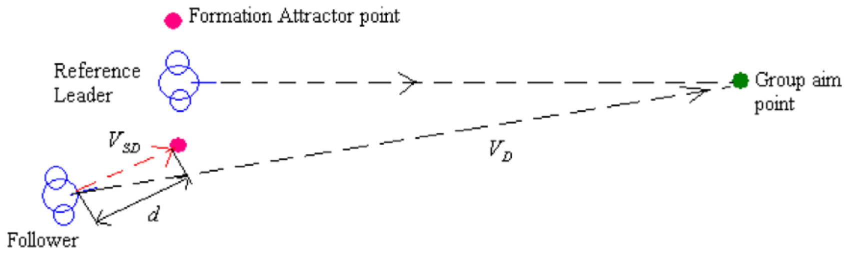

Fig. 10. The two desired velocity directions on a follower in the model: V_D (constant desired component, not proportional to distance shown) towards the group aim point, V_{SD} (proportional to d) towards the moving attractor point beside the reference leader.

3.3. Psychological repulsive forces between subgroups

The DEM principle treats every individual as an independent entity and simulates their motion by applying various forces separately on each one of them. This principle is modified to make the subgroup behaviour more realistic. Thus the following two algorithmic additions are made to the DEM model, treating subgroups as single entities. In a previous study with Crowd-DMX – summarised in Appendix B – it was shown that in a situation of contra-flow people (people in different groups whose paths cross) could unrealistically "psychologically bounce off each other". An algorithm was added so that individuals could take avoidance action. The same algorithm is applied here with the subgroup modelled as an entity.

3.3.1. Subgroup–subgroup interaction

The following algorithm is applied to every distinct subgroup pair which move towards different group aim points:

- The *geometric centre* of each subgroup is calculated by finding the arithmetic mean of the positions of the members:

$$C_X = \sum \frac{x_i}{n}, \tag{5}$$

$$C_Z = \sum \frac{z_i}{n}, \tag{6}$$

where (x_i, z_i) is the position of ith member of the subgroup, n is the total number of people in the subgroup.

- The *mean velocity* of each subgroup is calculated by finding the arithmetic mean of the velocities of the members.
- Modelling both subgroups as single units, the *closest point of approach (CPA)* is calculated using the routine for collision identification and avoidance (Appendix B). This algorithm is applied only if the subgroup centres are within 10 m of each other.
- Unit vector towards the CPA is calculated.
- Using the following equation, additional desired velocity components are added to each of the subgroup members opposite to the direction of CPA. These components are opposite for the two distinct subgroups in question:

$$F_{SS} = \frac{m_i k_{SS} V_{SSD}}{\tau_i d_{sgp}}, \tag{7}$$

where F_{SS} is the extra force added to each member of the subgroup, m_i and τ_i are constants as in Eq. (3), k_{SS} is the interaction constant, d_{sgp} is the distance between the subgroup centres, V_{SSD} is the desired velocity oriented away from the CPA.

Interestingly this force is inversely proportional to the distance between the two subgroups and hence causes the members to take corrective action more as they get closer to the other subgroup. A value of k_{SS} = 10 m was found to give realistic results.

3.3.2. Subgroup–individual interaction

A similar algorithm as mentioned above is implemented between each subgroup and lone individual persons travelling in different directions. The motive behind this is the tendency of individuals to walk around a subgroup and not between it. Thus the corrective force is only added to the individual and negligible psychological force is assumed on the subgroup encountering the individual.

The mean centre and mean velocity of the subgroup is calculated. Then knowing the position and velocity of the individual person, the CPA (closest point of approach) is found. The same equation (Eq. (7)) is used with desired velocity component away from the CPA and the extra force applied to the individual only. This interaction is calculated only if the distance between the subgroup and the individual is less than 8 m. Hence a realistic circumvention of the subgroup by the individual person takes place.

3.4. Results and validation

Taking the filmed videos as reference, the simulated scenarios for those real situations were tested and compared to video footage. There was generally good agreement between the videos and simulations with the modifications described above.

The validation procedure included a two stage approach:

(1) *Choice of interesting crowd scenarios from video footage:* The filmed video was browsed manually to choose specific situations of contra-flow of multiple subgroups. Interesting clips were saved as snapshots and the parameters including number of people, number of subgroups and physical settings were noted. The criteria for selection were: contra-flow of subgroups comprising 2–4, where people had to take avoidance action, disrupting the subgroup formation, which reformed when the path was clear again.

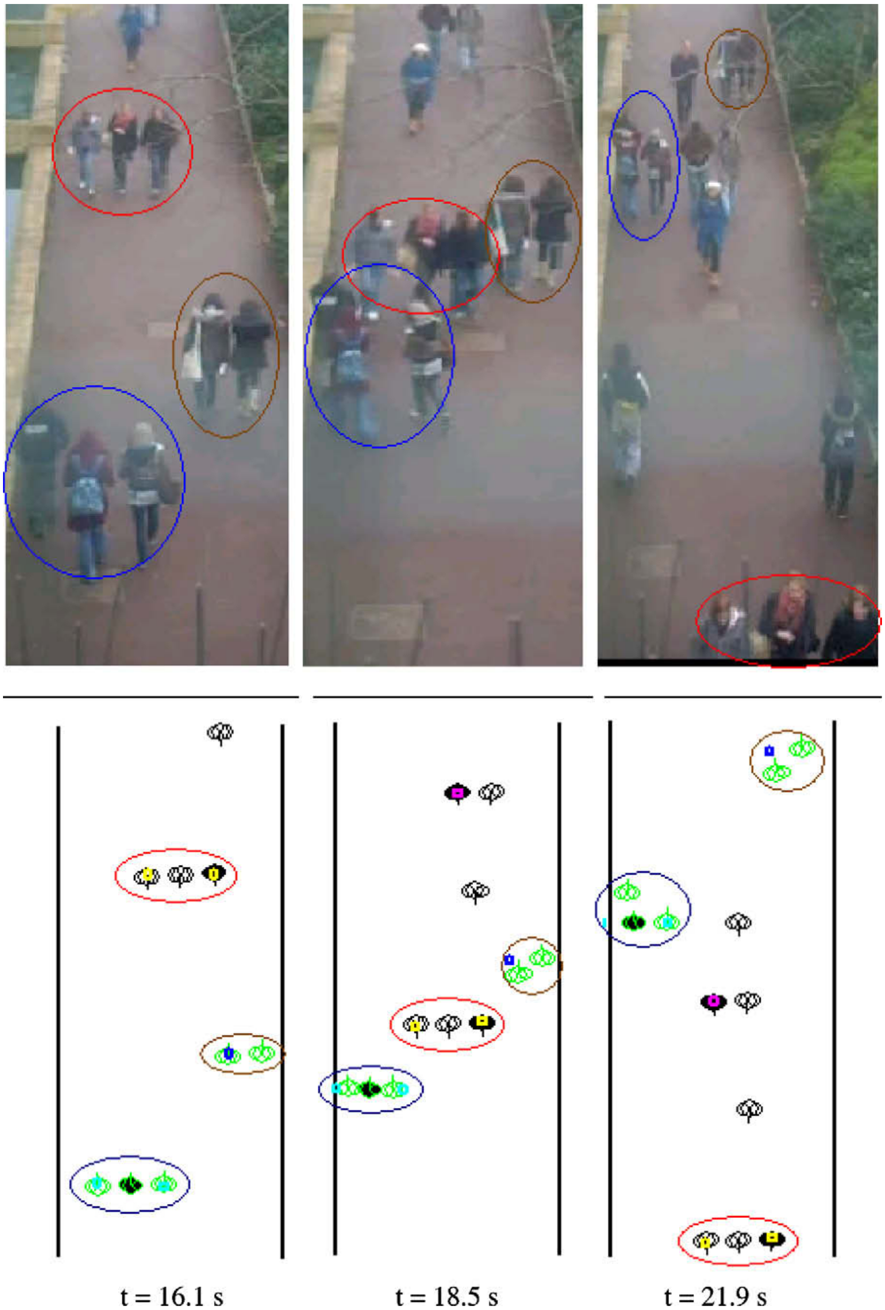

Fig. 11. Scenario 1 clips from simulation and corresponding real-life video-footage clips. Corresponding subgroups are ringed with same colour. Formation attractor points are shown for subgroups. Indicates avoidance action taken by subgroups in contra-flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. Scenario 2 clips from simulation and corresponding video-footage clips of the simulated situation. Observe individual circled brown moving around the subgroup circled red and observe avoidance of subgroups circled blue and red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2) *Simulation of chosen scenarios:* The chosen situations were then hard-coded as starting situations in the modified Crowd-DMX program with all the parameters saved beforehand. These test cases with initial settings coded in, were allowed to run according to the program's algorithm. The results shown by the simulations largely matched the video footages.

Three of the scenarios simulated are shown here, which demonstrate the validity of the algorithmic changes made:

3.4.1. Scenario 1 – Fig. 11

Fig. 11 shows a comparison of simulation to footage shot from Queen's Medical Centre bridge. It shows the contra-flow of a subgroup of three people against two subgroups of two and three people. It shows how the two subgroups allow the oncoming subgroup to go in between.

3.4.2. Scenario 2 – Fig. 12

This comparison also involves filmed clips from the QMC bridge. The simulation captures individuals moving around subgroups and subgroups avoiding each other.

3.4.3. Scenario 3 – Fig. 13

This is a scenario wherein multiple subgroups meet head on. This has been set up to represent a typical scenario which was observed on many occasions during filming. It is interesting to observe the realistic behaviour of large subgroups versus

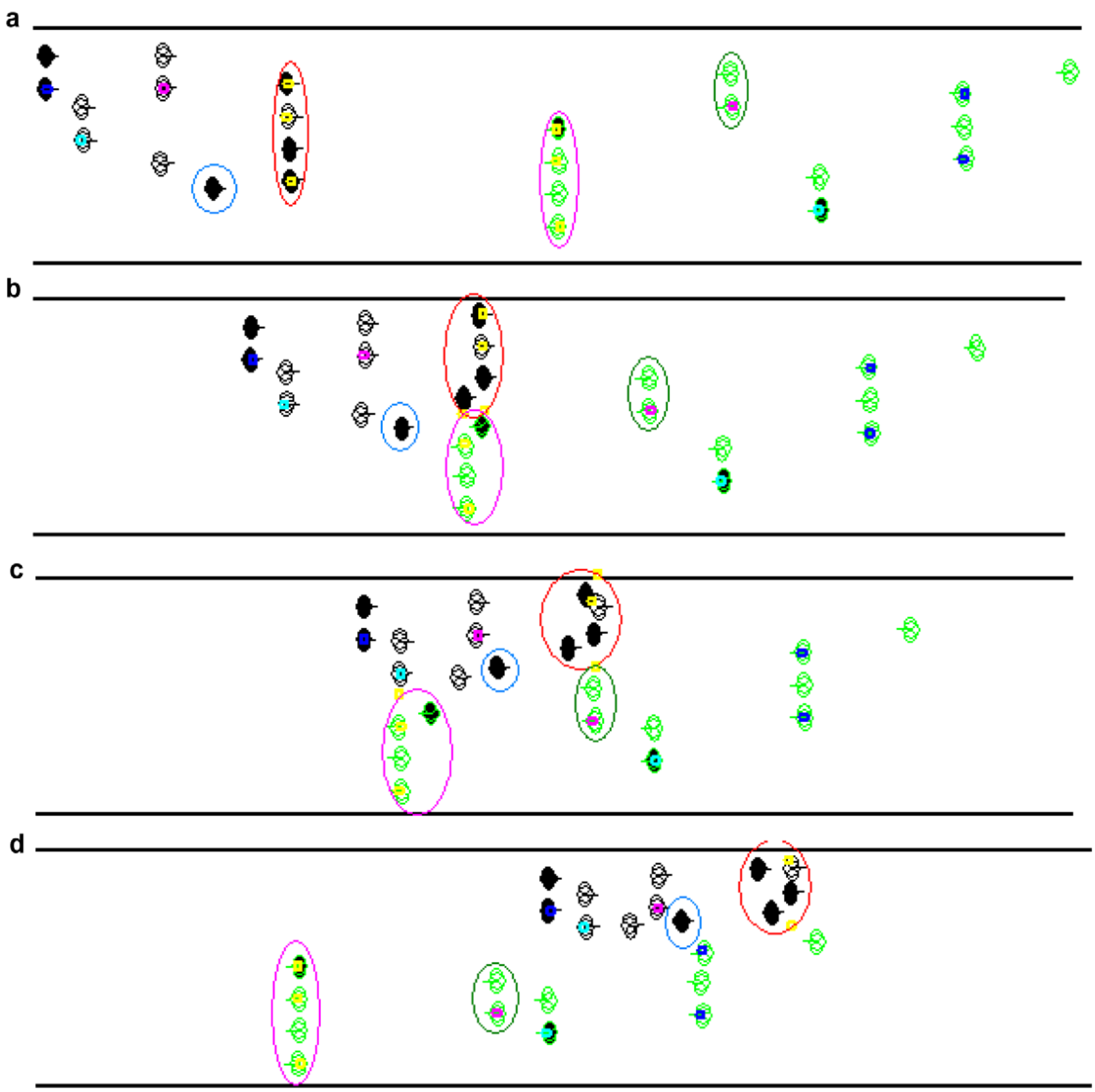

Fig. 13. (a) Scenario 3 simulation clip at time $t = 15$ s. Multiple subgroups meeting head on. (b) Simulation clip at time $t = 17.5$ s. Observe the curtailing of the subgroups circled red and pink. (c) Simulation clip at time $t = 19$ s. Observe the individual circled blue moving towards left to avoid people coming head on from the right. Also see the subgroup in red lining up partially in lack of space. (d) Simulation clip at time $t = 21.4$ s. Individuals realistically avoid splitting a larger subgroup as shown here. Larger subgroups accommodate themselves in order to stay together. Observe pink subgroup has realigned. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the behaviour of individuals. Note the tendency of large subgroups to slow down and change formation to stay close in less space. Note the ability of individuals to avoid large subgroups and go around them. Also note how subgroups reform after the avoidance. These natural tendencies have been realistically simulated by the program.

4. Conclusions

This paper investigates small subgroups of people within crowds and describes how their behaviour was incorporated into the CrowdDMX program. Initial comparisons of simulations and filmed crowds here highlighted the necessity to include subgroups in the CrowdDMX model. Further filming and observations of crowds were made in order to understand subgroup behaviour. The model was developed by incorporating moving 'formation attractor points', which hold small subgroups of people in formation. This enabled members of a subgroup to keep together while walking. Additional psychological repulsive forces were added to correct unusual splitting of subgroups and model the realistic movement of individuals around a subgroup.

The improvements were validated on a visual basis through simulation with the new code and direct comparison to the filmed footage. The developments are successful in creating subgroups and simulating their behaviour within crowds.

Although significant progress has been made to make the simulations reasonably realistic, there is still need for improvement. This paper focussed on the improvements made to incorporate subgroups in the DEM model for crowd dynamics. It is recommended that further filming is undertaken in several locations outside of the university so that the trends and patterns observed can be compared for more diverse types of crowds. Also more work needs to be done on simulating complex scenarios. The present model simulates the most logical outcomes while a realistic crowd can include more complex or contradictory behaviours over time, which might be incorporated with techniques of Artificial Intelligence.

Appendix A. Summary of CrowdDMX Model (Langston et al., 2006)

A.1. People and environment

In the model each person is represented by three intersecting circles at a position (x, z) and direction θ at time t. A number of different people types can be specified with a nominal size and a nominal desired velocity. The model applies a 2% random variation on characteristics for individuals (which avoids artificial "packing" in the model and better represents real life variation). The environment is defined by a number of wall elements and a sequential number of aim points each with a representative zone. Generally, the wall elements are impassable and the model includes the possibility of a wall affecting the desired velocity of people in the locality.

A.2. Forces

The psychological interaction force F_{PSY} acting between people i and j has been taken from Helbing et al. [32] and is shown in Eq. (A1). This acts normally between the person centres, where k_1 and k_2 are empirical constants, r is the sum of the people radii and d is the distance between person centres. A psychological radius can be specified for each person. Eq. (1) is applied once between persons i and j at time t. The psychological radius can be considered as a measure of "personal space". This is perhaps the most difficult part of the model in terms of realism. This will depend on the scenario and individual temperaments and will the subject of future studies. However, it is evident that realistic generic results can be obtained as is shown later:

$$F_{PSY} = k_1 \exp((r_{ij} - d_{ij})/k_2). \tag{A1}$$

On physical contact ($r > d$) the normal force F_N is modelled as a linear spring as in Helbing et al. [32] except that here each person is modelled as three circles. The force is shown in Eq (A2) where k_N is the normal spring constant. The sliding friction force F_T is modelled as a function of the relative tangential velocity, v_{RT}, at the contact as shown in Eq. (A3) where k_T is the tangential dynamic spring constant. This is similar to Helbing et al. [32] except that here the person geometry is different and rotation is modelled here. It should be noted that in CrowdDMX there are potentially two contact points between individuals due to the three-circle representation. Each contact point is modelled separately, where ik is one circle in person i and jk is one circle in person j:

$$F_N = k_N(r_{ikjk} - d_{ikjk}), \tag{A2}$$

$$F_T = k_T(r_{ikjk} - d_{ikjk})v_{RT}. \tag{A3}$$

In addition this study has included a physical damping force F_D as in Eq. (A4), somewhat analogous to particle interactions. It acts normally at the contact and is proportional to the normal relative velocity, v_{RN}. This could be significant in mass emergency evacuation situations. The magnitude of the damping parameter c_{DP} was selected by trial and error obtaining simulations which looked reasonably realistic:

$$F_D = c_{DP} v_{RNikjk}. \tag{A4}$$

A.3. Moment from contact

This study has incorporated moments on the people resulting from physical contact as shown in Eq. (A5), where M_c is the moment, R_{ic} is the radial vector from the person centre to the point of contact, and $\times$ is the vector cross product:

$$M_c = R_{ic} \times (F_N + F_T + F_D). \tag{A5}$$

This results in an angular acceleration. The orientation of individuals is significant here.

A.4. Motive moment

A motive moment, Eq. (A6), has also been incorporated to model how an individual will turn to face the desired direction, where M_M is the motive moment, k_M is an empirical spring constant, θ is the directional angle, i indicates current value and D indicates desired value. This desired direction is taken as the direction to the aim point for the highest zone number containing the person:

$$M_{Mi} = k_M(\theta_i - \theta_D). \tag{A6}$$

The constant in Eq. (A6) is difficult to gauge. Several values have been tried here in trial simulations along with a maximum allowed angular velocity. In some the people turned too slowly and in others they oscillated about the desired direction. The simulations appear reasonable here, but further consideration should be given to Eq. (A6).

A.5. Motive force

The motive force F_M is calculated from Eq. (A7), where V_D and V_i are the desired and actual velocities of person i, τ_i is the characteristic time (an empirical value which determines how quickly a person responds to a situation) and m_i is the mass of person i:

$$F_M = m_i(V_d - V_i)/\tau_i. \tag{A7}$$

A.6. Motion

The resultant translational and angular acceleration is calculated for each person at time t from the resultant force and moment. The translational and angular velocities and position are estimated at $t + \Delta t$ using standard numerical integration methods. The time-step Δt is a critical parameter. Too large and the results are inaccurate, too small and the simulation takes a long time and rounding errors may result as well. Trial simulations were carried out here using smaller time-steps until the results were consistent.

Table A1. Principal Simulation Data.

Parameter	Value		Source
People	Type 1	Type 2	General estimates
Radius “torso” (m)	0.21	0.2	
Radius “shoulder”	0.14	0.13	
Radius “psychological” (not sum of above)	0.34	0.32	
Mass (kg)	80	70	
Moment of inertia (kg m^2)	4	3.5	
Desired velocity (m/s)	1.5	1	
Characteristic time (s)	0.5	0.5	Helbing et al. [32]
Max velocity (m/s)	3		
Max angular velocity (rad/s)	0.4		
Force equation constants			
k_1 (N)	2000		Helbing et al. [32]
k_2 (m)	0.08		Helbing et al. [32]
k_N (N/m)	1.2×10^5		Helbing et al. [32]
k_T	$0.5k_n$		Estimate from simulations
k_M (Nm/rad)	50		Estimate from simulations
c_{DP} (Ns/m)	2000		Estimate from simulations
Modelling constants			
Time-step (s)	0.002		

Appendix B. Avoidance model summary (Smith et al., 2009)

The model described in Appendix A works well for large crowds where people are generally travelling in the same direction. Its main limitation, however, is that when people are travelling in different directions there is no algorithm in the program which enables them to avoid each other and as a result unrealistic "collisions" occur and people "bounce off each other's psychological space" before continuing towards their aim points. To improve the simulation an avoidance algorithm was incorporated by adding an extra component to the desired velocity of an individual when a potential collision is detected.

Consider two individuals A and B moving towards each other. A potential collision is predicted by calculating the relative velocity of B with respect to A. Then the routine calculates the closest point of approach of B towards A, i.e. the closest possible distance between A and B predicted on their current velocities. Next a unit vector, **u**, is calculated from the closest point of approach towards A. This is the direction in which the extra desired velocity component is added, for each A and B, in opposite directions. Thus any avoidance action is taken in opposite directions. The additional desired velocity component is used in Eq. (A7) (see Figs. B1–B3).

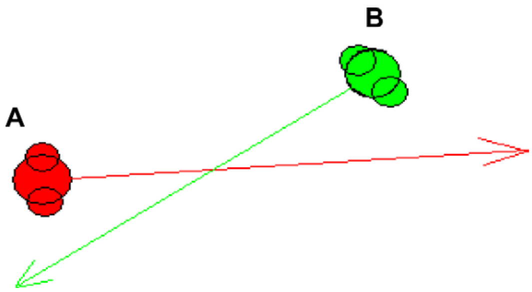

Fig. B1. A possible situation where the paths of two people cross and the likelihood of a collision must be established.

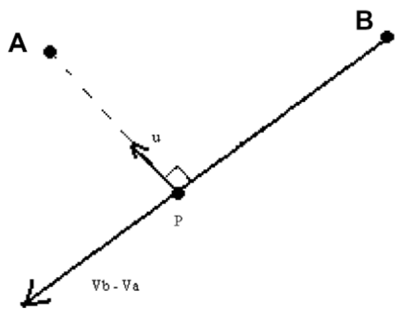

Fig. B2. Velocity of person B relative to person A. The vector **u** is added to the desired velocity of both persons A and B (in opposite directions).

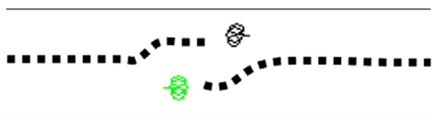

Fig. B3. Effect on simulation of avoidance algorithm. Shows paths taken in case of contra-flow.

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